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Tools for Energy Footprint Assessment in Urban Water Systems

S. Baki[a,*], C. Makropoulos[a]

[a]*Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens (NTUA), 5, Heroon Polytechneiou, 157 80, Athens, Greece*

Abstract

In this research we examine the extension and application of UWOT, the Urban Water Optioneering Tool [1], for the modelling of water - energy interactions within water supply systems. The tool was tested in the complex urban water system of Athens by simulating the current water-energy situation and attempting to assess the effect of potential interventions, mainly focusing on hydropower generation, with the aim of developing water-energy roadmaps. The paper also discusses the role of such integrated modelling tools and methodologies in sustainable strategic planning and efficient management at the city level.

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Keywords: Energy footprint; energy recovery; intervention assessment; renewable energy generation; urban water systems; water supply; water-energy nexus.

1. Introduction

Water and energy are natural resources inextricably linked with each other; the interrelationship and interactions between them are commonly referred to with the term "water – energy nexus". The identification and analysis of linkages and trade-offs between water and energy has gained significant attention in recent years as seen from various current international practices and guidelines [2,3,4,5] and it is now widely acknowledged that a combined and integrated approach is required to attain sustainable resource management [6]. Specifically in urban water systems (UWSs), energy can be consumed through all the different phases of the urban water cycle (UWC), including the source for water abstraction, water conveyance in the external aqueduct network, water treatment, water distribution in the internal distribution network, end-use, wastewater treatment, wastewater reuse and effluent discharge [7,8,9,10].

* Corresponding author. Tel.: +30-210772-2840; fax: +30-210772-2832.
E-mail address: s_baki@mail.ntua.gr

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The energy component of the UWC is also of rising importance due to the increasing energy use and energy prices. Particularly for water utilities, energy use represents, in most cases, the highest operating cost after manpower [11]. It should therefore be a main priority and challenge for the water industry to achieve combined resource efficiency, for both water and energy in UWSs.

To address this issue there is a need for tools that are able to estimate the energy footprint of the entire UWC, from source to tap to final discharge. Such tools would enable the investigation of different type of potential policies and interventions on the UWS under a synergistic viewpoint. In fact various potential energy related interventions can be applied to the different phases of the UWC [11,3,12,10,13], including interventions specifically targeting water distribution and conveyance [14,15,16], wastewater [17] and end-use phases [18,4,2]. These interventions can be further categorised in different groups, such as technical and operational, or water demand management interventions, interventions that are implemented at a water company, end-user or local level. In this research we examine the further development of the Urban Water Optioneering Tool, UWOT [1], towards modelling of water – energy interactions within UWSs and its potential for providing a common platform for the combined assessment of water and energy in the UWC. The proposed methodology was tested in the Athens UWS and for the purposes of the current work the analysis focused on the external water supply system (WSS). We discuss the use of the specific model in investigating the effect of various energy related interventions and developing sustainable urban water management roadmaps.

2. Model description and development

2.1. General description

UWOT is a tool that simulates the entire UWC from source to tap and disposal in a common modelling environment. Unlike most urban water models that use a hydraulics-based conceptualisation of the urban water network simulating actual water flows, UWOT uses an alternative demand-orientated approach based on demand signals [1]. More specifically the model generates aggregates and transmits a demand signal starting from household water appliances and moving towards the source [19]. This urban metabolism approach can facilitate the assessment of both demand and supply side interventions in UWSs [1]. Fig. 1 shows the representation of the UWC in UWOT. The upper part of the right panel represents the external WSS, including water source abstraction, raw water conveyance and treatment, whereas the lower part represents the internal water system, including the end-user phase generating the demand, wastewater and runoff treatment and disposal. UWOT has the ability to simulate different household types, conventional, as well as decentralised water technologies, including rainwater harvesting and water recycling schemes; users can also model in UWOT individual phases of the UWC or the entire cycle [1].

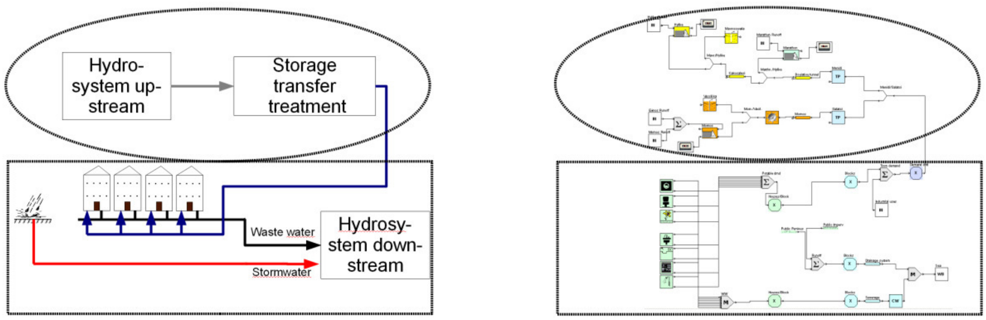

Fig. 1: (a) Simplified representation of the UWC (left panel), (b) UWOT representation of the UWC (right panel). (Source: [1])

2.2. Development of energy components & calculations

Energy consumption or energy production is calculated by various UWOT components of the external water system, including hydro turbines (HD), aqueducts (AQ) when these represent aqueduct sections with one or more pumping stations, groundwater sources (GW) and treatment plants (TP). For all these components the energy use per unit volume (kWh/L) or else specific energy is specified in UWOT's "technology library" and the energy consumed or produced in each time step is then estimated by multiplying this value with the incoming demand.

$$E = \varepsilon \times V \tag{1}$$

E is the energy consumption or production (kWh), ε the specific energy consumption or production (kWh/l) and V the volume of water (per model time step) (l).

Up to now the simplifying assumption of constant values for specific energy was made in UWOT. However, in reality there are cases where specific energy varies considerably. This variation is of particular importance for hydropower production where specific energy varies with flow, as well as with changes of upstream and/or downstream hydraulic head in the case of reservoirs within the hydrosystem. The power output of a hydropower plant (HPP) is given by the following equation:

$$P = \rho\, g\, Q\, H_{net}\, n \tag{2}$$

In equation 2 P is the produced power by the HPP (W), ρ the density of water (kg/m^3), g the acceleration of gravity (m/s^2), Q the flow passing from the turbine (m^3/s), H_{net} the net head at turbine (m) and n the total HPP efficiency (turbine, generator, transformer).

For the purposes of the current work, which focuses on the water-energy nexus, energy related calculations in UWOT have been further refined in order to address this issue. Specifically the hydro turbine component (HD) has been modified so that instead of including a constant specific energy consumption / production value, the produced power in each time step is calculated by the following third degree bivariate polynomial equation:

$$P = a + bQ + cH_{HWL} + dQ^2 + fH_{HWL}^2 + gQ^3 + hH_{HWL}^3 + iQH_{HWL} + jQ^2H_{HWL} + kQH_{HWL}^2 \tag{3}$$

Q is the flow passing from the turbine (m^3/s), H_{HWL} the head water level, i.e. the water level of the upstream reservoir (m) and a, b, c, d, f, g, h, i, j, k are the polynomial coefficients.

By adopting this methodology the user has the flexibility to include more or less level of detail in the energy calculations related to the HD component depending on the available information and data, as well as the specific conditions in each HPP, such as the existence or not of an upstream reservoir. In the most simplified case equation 3 can be reduced to equation 1.

3. Model application / case study

3.1. Hydrosystem description

The model was tested in the intricate UWS of Athens that serves a population of approximately 4,300,000 people. The analysis focused on the external urban WSS, i.e. the water conveyance phase up to the city's four water treatment plants (WTPs). The Athens external WSS extends over an area of around 4,000 km^2 including both surface and groundwater resources. The hydrosystem comprises an extensive network of surface water reservoirs, boreholes, aqueducts, pumping stations, HPPs and WTPs and is characterised by a high level of complexity [20,21]. The majority of the water used for supplying the area of Athens comes from surface water sources and specifically from the reservoirs of Mornos and Evinos. The natural lake of Hylike and Marathon reservoir are mainly used as auxiliary water sources; under normal conditions a small fraction of water is abstracted. Groundwater from different borehole groups is also used as a back-up water source. The external aqueduct network mainly includes two main branches, the north branch an energy intensive branch conveying water from Hylike, Marathon and different borehole groups and the south branch conveying water through gravity from Evinos and Mornos reservoirs. Besides the primary aqueduct network, the hydrosystem also includes connecting and auxiliary aqueducts, most important of which is the Marathon connecting aqueduct that links the south and north aqueduct branches. During recent years energy dissipation works are being converted along the south branch and currently six small HPPs are in operation.

3.2. Model development and assumptions

In this work we developed a model of the external WSS of Athens up to the four WTPs and run the model for eight historical years with a monthly time step. The model was calibrated against Mornos and Hylike water levels, water abstractions per source and actual hydropower production from the existing HPPs. The calibration exercise attempts to capture current decisions of the water company related to the operation of the Athens hydrosystem. The overall aim for developing the specific model is to facilitate the assessment of different potential future energy-related interventions that have been identified for the Athens hydrosystem.

The structure of the Athens WSS has been set-up in UWOT so that the resulting schematisation resembles as much as possible the actual UWS (Fig. 2). Since the particular hydrosystem is quite complex some simplifications and assumptions were necessary to reduce model complexity. For example, some auxiliary aqueduct sections were ignored as they are rarely used, only the most significant borehole groups were included and potable water transfers between WTPs were ignored. The representation of the Athens external water supply network in UWOT employs various model components, including aqueduct sections (AQ), surface water reservoirs (SW), groundwater sources (GW), hydro-turbines (HD), network splitters (SP), etc. For each component different brands were specifically developed for the adequate representation of the various actual components of the Athens WSS. Each UWOT component brand was assigned with appropriate technical specifications; these values were either taken directly from water company data or literature. Especially regarding technical specifications of the existing HPPs power-discharge (P-Q) curves or power-discharge-water level (P-Q-H) curves, in the case of reservoirs, were constructed for each of the five facilities operated by the Athens Water Supply and Sewerage Company (EYDAP). In each case available data were used, such as manufacturer’s turbine efficiency curves and plant performance evaluation data.

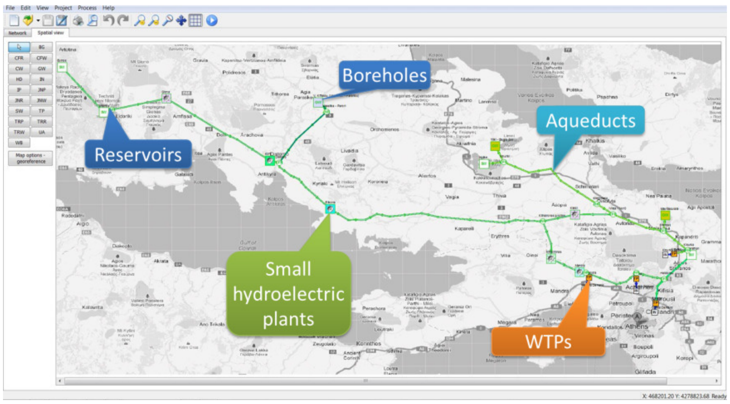

Fig. 2: UWOT schematisation of the Athens external WSS (Spatial / GIS view)

Since no data were available for the HPP operated by the Public Power Corporation (PPC), a constant specific energy production value was used based on actual energy production data. Having completed the network schematization the model was run for eight hydrological years with monthly historical timeseries for the period 2002-2010. Historical monthly timeseries for catchment runoff, reservoir precipitation and evaporation were used in order to create net inflow timeseries for each reservoir. Water demand data used include the historical inflows at each of the four WTPs, raw water demand from the communities along Mornos and Hylike aqueduct network, historical irrigation abstractions from Hylike Lake and the environmental flow released from Evinos reservoir.

4. Model results

4.1. Water balance

The model was initially calibrated to match the historical water balance in terms of reservoir water levels, as well as water abstractions per source. Model parameters calibrated for this purpose are the splitter component values. Splitters are UWOT components of particular importance as they distribute the water demand signals to different water sources of the hydrosystem depending on the water availability in each water source [1]. For the particular application and network schematisation five splitters have been used in total, two splitters on the main aqueduct network defining the demand signals going to the northern and southern branches and three splitters corresponding to each of the three borehole groups. Model results were compared against historical water abstractions and Mornos and Hylike net storage. Table 1 presents a comparative analysis of the water balance between UWOT and available historical data by comparing average annual values of abstractions from the main reservoirs calculated for the eight hydrological years. Fig. 3 shows the fluctuation of the modelled versus the historical net reservoir storage for (a) Mornos and (b) Hylike for the entire simulation period. The Nash-Sutcliffe coefficients were calculated for simulated net storage and are equal to 0.88 and 0.93 for Mornos reservoir and Hylike Lake respectively.

Table 1. Modelled and historical annual water abstractions per source.

	Mornos (and Evinos)	Evinos (to Mornos)	Hylike
UWOT (hm^3/y)	430.61	249.30	35.95
Historical (hm^3/y)	430.91	247.61	26.38
% Difference	-0.07	0.68	36.27

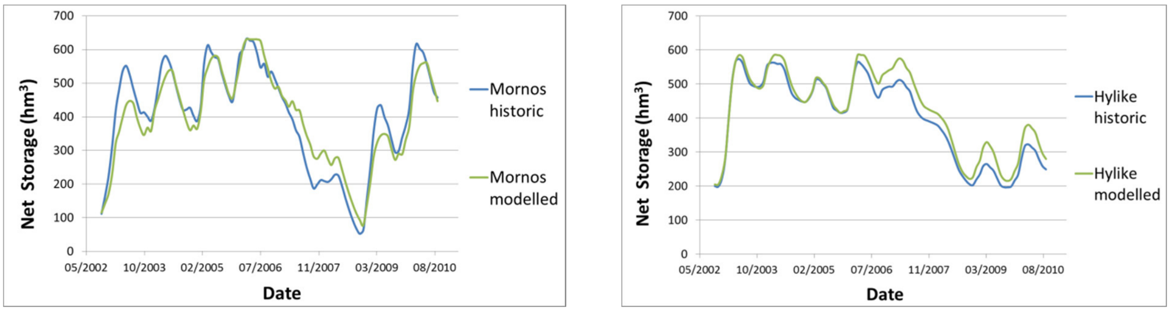

Fig. 3: Modelled vs. historic net reservoir storage for (a) Mornos reservoir and (b) Hylike Lake

From the presented results it can be observed that the actual water abstractions from Hylike are quite lower than the simulated ones. According to Makropoulos et al. [21] in order to achieve 99% reliability in the Athens UWS over the longer term for the current levels of water demand, abstractions from Hylike should amount to approximately 70 hm^3 per year. This significant difference in actual and optimised abstractions indicates that the water company is currently operating the system with minimal abstractions from Hylike in favour of lower energy costs, also resulting however, at the same time, in lower system reliability in the longer term. The differences in the fluctuation of Hylike net storage (Fig. 3b) can be probably attributed to the way Hylike leakage is estimated by UWOT that probably slightly underestimates it. Leakage from Hylike is a significant component of the reservoir's water balance and it is quite difficult to model since it doesn't have a constant correlation to the lake's water level, but this relationship varies seasonally [20]. Despite this, the graph and the value of the Nash-Sutcliffe coefficient suggest an overall good fit with the observed values. Mornos modelled net storage fluctuation (Fig. 3a) together with a Nash-Sutcliffe coefficient value of 0.88 indicate a satisfactory model behaviour. Overall the results suggest an acceptable model performance in terms of simulating the historical water balance taking into account the various assumptions adopted during model development.

4.2. Energy balance

Following the satisfactory water balance calibration the model was calibrated in terms of hydropower production. As calibration parameters the “HD availability” factors for the six HPPs were used. UWOT calculates the theoretical energy production according to equation 3 assuming 100% plant availability. However, in reality HPPs operate for a fraction of the time due to reasons such as maintenance, failures or other low level operational decisions. To address this issue the parameter “HD availability” has been introduced in UWOT to account for this “non-operational time”; its value corresponds to the percentage of the time each HPP is operational. Table 2 presents simulated and historical average annual energy production from each of the six HPPs, (five operated by EYDAP and one by the PPC), the corresponding “HD availability” values used, as well as modelled mean annual energy consumption for pumping and groundwater abstractions. No historical energy consumption data were available for comparison reasons at the time of model development. Fig. 4 displays the modelled average seasonal variation in energy consumption and renewable energy production by the existing HPPs operated by EYDAP.

Table 2. Modelled and historical energy production and consumption.

	Hydropower Production						Energy Consumption	
Energy production / consumption	Evinos Env. HP	Kirfi HP	Elikona HP	Kithaironas HP	Mandra HP	Giona HP (PPC)	Pumping	Groundwater
UWOT (GWh/y)	4.851	4.937	3.850	5.048	3.520	40.370	55.359	3.631
Historical (GWh/y)	4.837	4.936	3.831	4.995	3.635	40.690	-	-
% Difference	0.30	0.02	0.48	1.05	-3.18	-0.79	-	-
HD Availability	0.85	0.80	0.74	0.54	0.95	0.85	N/A	N/A

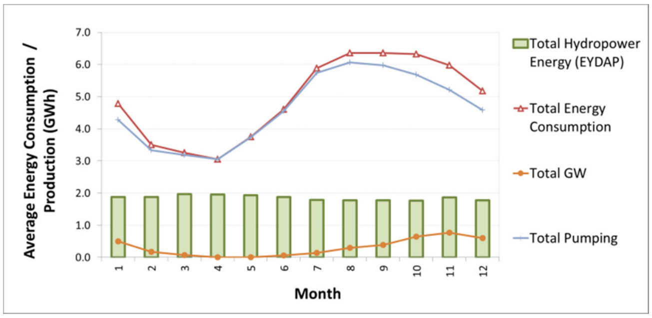

Fig. 4: Average modelled monthly energy consumption and production along the external WSS

The comparison against actual hydropower production data highlighted the fact that Kithaironas HPP produced significantly lower energy in comparison to its hydropower potential. Kithaironas is the only HPP that has two turbines and it is suspected that possibly for a certain percentage of time only one of the two turbines is actually operated by the water company. Overall, model results in terms of energy production are considered quite satisfactory and they do highlight the significant hydropower potential along the Athens external WSS. Energy consumption model estimates for water pumping and groundwater abstractions are relatively low due to the hydrosystem operational policy applied by EYDAP that minimises abstractions from the energy intensive aqueduct branch and groundwater sources and maximises abstractions from Mornos and Evinos reservoirs.

5. Investigation of energy related interventions

Various energy production and energy saving interventions have been identified for the Athens UWS from various literature sources [22,23], as well as in collaboration with EYDAP. Table 3 presents some of these interventions, mostly focusing on hydropower schemes. The potential actions have been grouped into different phases according to their implementation timeframe.

Table 3. Identified energy-related interventions.

	Step 1: Immediate	Step 2: Short-term	Step 3: Long-term
Proposed Intervention	• Pump replacement (Kiourka) • Operational improvement of existing HPPs • New HP Klidi	• New HPP Helidonou	• New HPP Outlet of Evinos – Mornos tunnel

Following the successful simulation of the historical scenario a modelling experiment was carried out with the developed model in conjunction with 100-year synthetic timeseries statistically consistent with historical data, which were used to create the net inflows for the hydrosystem's reservoirs. Current water demand data were used, including demand for the four WTPs, raw water demand, Hylike irrigation and Evinos environmental flow. For the specific application it is assumed that water demand remains constant at current levels throughout the simulation period and a constant demand monthly pattern was generated. The effect of each set of interventions on the UWS's energy footprint was estimated at each implementation phase through the use of selected performance indicators. For this analysis we have examined (a) the "renewable energy fraction", i.e. the renewable energy generated over the total energy consumed (Fig. 5a) and (b) the "energy intensity" defined as the amount of energy required per unit water delivered (Fig. 5b). The two graphs in Fig. 5 demonstrate the evolution of the two selected indicators for the Athens external WSS through the different intervention phases that can be translated into steps of a possible water-energy roadmap for the particular hydrosystem. The total energy intensity, shown with a red line, is only affected by the one energy saving intervention examined, whereas the net energy intensity, shown with a blue line, is affected by the various energy production interventions applied.

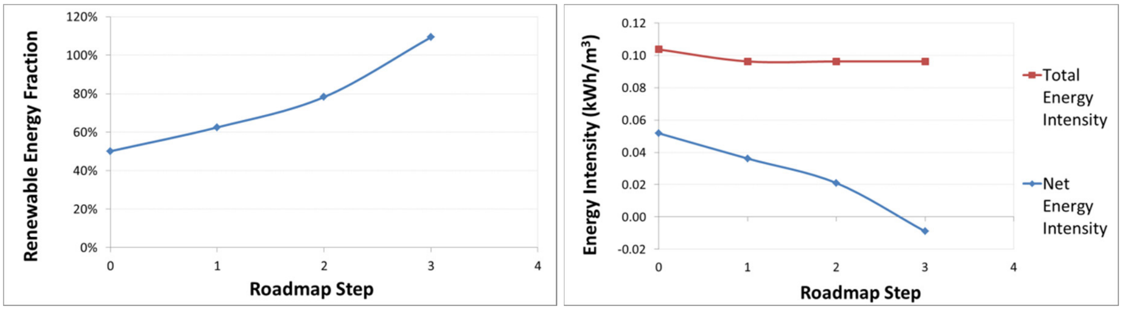

Fig. 5: Evolution of (a) Renewable energy fraction and (b) Energy intensity for possible water-energy Roadmap

6. Discussion and conclusions

The model developed in this work was able to adequately simulate the historical situation, both in terms of water and energy balances. The modifications and improvements applied to UWOT in terms of energy related calculations and model components expanded further the model's capabilities in representing water energy interactions within the UWC. In particular, the improvements implemented in the calculations of hydropower production are considered to provide considerably increased accuracy in energy production model estimates as the effect of discharge and reservoir water level variations is now captured. The preliminary results of the impact of selected energy related interventions indicate that there is significant energy recovery potential through hydropower generation along the Athens external aqueduct system. An example of a potential water energy roadmap for the Athens WSS was demonstrated. The current analysis and examined interventions have focused on the Athens external WSS. However, it would be of particular interest to expand the analysis downstream the WTPs in order to incorporate Athens' entire UWC and investigate the water-energy nexus through all the cycle phases. The complete urban UWC model can facilitate the exploration of additional broader hydrosystem interventions, such as water reuse and water demand management measures, and assess their effect on the system's energy footprint.

The current analysis demonstrates that the presented tool and methodology could enable the identification of the most promising and effective hydrosystem interventions and the estimation of the hydrosystem's potential for improvement in terms of the water-energy nexus. This methodology can lead to the development of sustainable roadmaps for UWSs. Overall the research aims to demonstrate that tools such as UWOT, that facilitate an integrated assessment of water and energy within UWSs, are able to capture interrelations between water and energy and evaluate potential interventions and policies by quantifying their effects on the UWC. Such tools can therefore play an important role in sustainable strategic planning and efficient management at the city level, especially if coupled with socio-economic scenarios through integrated modelling approaches that attempt to capture the entire socio-technical UWS, as demonstrated in the work described by Baki et al. [24], or even combined with urban growth models [25]. As current sector policies exhibit high degree of fragmentation such integrated tools can address the gap in integrated policies for addressing sufficiently the water - energy nexus in order to minimize negative trade-offs and maximize synergies between water and energy.

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